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Event shapes and azimuthal correlations in Z + jets events in pp collisions at $\sqrt{s} = 7$ TeV[☆]

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ABSTRACT

Measurements of event shapes and azimuthal correlations are presented for events where a Z boson is produced in association with jets in proton–proton collisions. The data collected with the CMS detector at the CERN LHC at $\sqrt{s} = 7$ TeV correspond to an integrated luminosity of 5.0 fb^{-1} . The analysis provides a test of predictions from perturbative QCD for a process that represents a substantial background to many physics channels. Results are presented as a function of jet multiplicity, for inclusive Z boson production and for Z bosons with transverse momenta greater than 150 GeV, and compared to predictions from Monte Carlo event generators that include leading-order multiparton matrix-element (with up to four hard partons in the final state) and next-to-leading-order simulations of Z + 1-jet events. The experimental results are corrected for detector effects, and can be compared directly with other QCD models.

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1. Introduction

A detailed study of the production of a Z boson in association with jets in pp collisions at the CERN Large Hadron Collider (LHC) is of great interest. Measurements of this process can be confronted with the predictions of perturbative quantum chromodynamics (QCD) at the highest accessible energies and for a broad range of kinematic configurations. Considerable theoretical progress has been made in this field, such as developments in next-to-leading-order (NLO) calculations for up to four hard partons produced in association with a Z boson [1], NLO predictions for Z + 1-jet production that can be interfaced to parton shower (PS) approximations [2–6], and leading-order (LO) multiparton matrix-element (ME) event generators such as ALPGEN [7], MADGRAPH [8], and SHERPA [9], with provision for PS development. In addition, Z + jets production corresponds to a major background to many other processes at the LHC, such as the production of top quarks, and it is important in searches for supersymmetric particles and Higgs boson physics. An improved understanding of Z + jets production over the largest possible regions of phase space can therefore provide a helpful tool for extracting small signals.

Previous studies of angular correlations between the Z and the “leading” jet (the one with the largest p_T) and between the two jets of largest p_T have been reported at the Tevatron by the D0 Collaboration [10] and at the LHC by the ATLAS Collaboration using

36 pb^{-1} of integrated luminosity [11]. In this Letter, the comparison of models with data for highly boosted Z bosons with $p_T^Z > 150 \text{ GeV}$ is of particular interest. This region of phase space is critical in searches for new phenomena that are based on a large apparent imbalance in the total transverse momentum. Such imbalance can be produced, e.g. by the $Z \rightarrow \nu\nu$ standard model (SM) background. The uncertainty of this background contribution is limited by the accuracy of current Monte Carlo (MC) models, which can be improved through studies of leptonic ($\ell^+\ell^-$) decays of Z bosons and their correlations with the associated jets.

In addition to azimuthal distributions, we provide the first measurements of variables that categorize the topological structure of Z + jets events. Multijet production at e^+e^- and ep colliders was used in the past to tune parton showers and fragmentation functions in MC event generators, as well as to measure the values of the strong coupling constant [12–16]. A set of event shape variables suitable for hadron colliders has been proposed in Ref. [17], which provides resummed perturbative predictions at next-to-leading-log (NLL) for these variables. A measurement of event shapes in multijet events was reported recently by the Compact Muon Solenoid (CMS) Collaboration [18].

This Letter extends measurements of angular correlations and event shapes in Z + jets events by probing the features of final states containing $Z \rightarrow \ell^+\ell^-$ decays, where $\ell = \mu$ or e. Such final states, often referred to as Drell–Yan (DY), include contributions from γ^* and Z/ γ^* interference terms arising from the irreducible background of virtual photons (γ^*) from $q\bar{q} \rightarrow \gamma^* \rightarrow \ell^+\ell^-$ processes. The data were collected with the CMS detector at a center-of-mass energy of 7 TeV, and correspond to an integrated

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luminosity of 5.0 fb^{-1} . The observed angular distributions and event shapes in $Z + \text{jets}$ production are compared with predictions from several MC generators, and comprise the first study of this kind to be reported at the LHC.

2. CMS detector

The origin of the CMS coordinate system is chosen at the center of the detector, with the z axis pointing along the direction of the counterclockwise proton beam. The azimuthal angle is denoted as ϕ , the polar angle as θ , and the pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter that produces an axial magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/plastic-scintillator hadronic calorimeter (HCAL) are positioned within the field volume. Iron and quartz-fiber hadronic calorimeters are located outside the magnetic field volume, within each endcap region of the CMS detector, at $3 < |\eta| < 5$. Muons are measured using gas-ionization detectors embedded in the flux-return yoke outside of the solenoid. A detailed description of the CMS detector can be found in Ref. [19].

3. Monte Carlo simulation

All production processes of concern, namely the $Z + \text{jets}$ signal and backgrounds corresponding to top–antitop quark pairs ($t\bar{t}$), dibosons (WZ, ZZ, WW), single top, and $W + \text{jets}$ events are generated with MADGRAPH (version 5.1.1.0) [8], which provides up to four-parton final states and is interfaced to PYTHIA (version 6.4.24) [20] using the Z2 tune [21] to implement showering and hadronization of the partons. The CTEQ6L1 [22] parton distribution functions (PDF) are chosen for these calculations. Alternative models for signal include (i) SHERPA (version 1.3.1) [9] (with up to four-parton final states) using the CTEQ6m PDF [22] and the default tune, (ii) POWHEG [2–5] for generating $Z + 1\text{-jet}$ events at NLO using the CT10 PDF [23] and interfaced to PYTHIA (version 6.4.24) with the Z2 tune for parton showering and hadronization, and (iii) stand-alone PYTHIA (version 6.4.24) with the Z2 tune. The cross sections for electroweak Z and W boson production are normalized to match the next-to-next-to-leading-order (NNLO) prediction obtained with FEWZ [24] and the CTEQ6m PDF. The $t\bar{t}$ cross section is normalized to the next-to-next-to-leading-log (NNLL) calculation from Ref. [25]. NLO precision obtained from MCFM [26] with CTEQ6m PDF is used for the cross section for diboson (WZ, ZZ, WW) and single top processes.

The detector response is simulated using a detailed description of the CMS detector based on the GEANT4 package [27], and the MC simulated events are reconstructed following the same procedures as used for data. During the data taking, an average of ten minimum-bias interactions occurred in each bunch crossing (pileup). The prevailing beam conditions are taken into account by reweighting the MC simulation to match the spectrum of pileup interactions observed in data.

4. Event selection and reconstruction

Event selection starts by requiring two high- p_T leptons at the trigger level. For muons, this corresponds to an online p_T threshold of 13 GeV (17 GeV during periods of higher instantaneous luminosity) for the muon of largest p_T (leading muon), and 8 GeV for the subleading muon. For electrons, the corresponding trigger thresholds are 17 GeV and 8 GeV. Offline, muon candidates are reconstructed through a simultaneous fit to the hits recorded in the tracker and the muon detectors [28]. Electrons are reconstructed

using both calorimeter and tracking information [29]. The two leptons of largest p_T (i.e. the two leading leptons) in the event are required to be of opposite electric charge and have $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$, and invariant mass satisfying $71 < m_{\ell\ell} < 111 \text{ GeV}$ to be considered Z boson candidates. The lepton candidates are also required to be isolated from other energy depositions in the event. In particular, an isolation variable is computed using the scalar sum of transverse momenta of tracks and calorimetric energy depositions within a cone defined by $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the direction of the lepton, where $\Delta\phi$ is in radians. The contribution from pileup to this p_T sum is estimated from the distribution of the energy per unit area in the η – ϕ plane in each event [30], and is subtracted from the calculated sum. This corrected sum is required to be less than 15% of the measured p_T of the lepton. Lepton reconstruction efficiencies are determined using simulation, and corrected for differences between data and simulation using the “tag-and-probe” technique described in Ref. [31].

The inputs to the CMS jet clustering algorithm are the four-momentum vectors of the particles reconstructed using the particle-flow (PF) technique [32,33], which combines information from different subdetectors. Jets are reconstructed using the anti- k_T clustering algorithm [34], with a size parameter of $R = 0.5$, by summing the four-momenta of individual PF particles according to the FASTJET package of Refs. [35,36].

The reconstructed PF candidates are calibrated to account for any nonlinear or nonuniform response of the CMS calorimetric system to neutral hadrons. Charged hadrons and photons are sufficiently well-measured in the tracker and in the ECAL, and do not need such corrections. However, the resulting jets require small additional energy adjustments, mostly from thresholds set on reconstructed tracks and from the clustering procedure in the PF algorithm, but also from biases generated through inefficiencies in reconstruction. Jet-energy corrections are obtained using simulated events that are generated with PYTHIA (version 6.4.22), processed through a CMS detector simulation based on GEANT4, and then combined with measurements of exclusive two-jet and photon+jet events from data [37]. By design, jet energy corrections bring reconstructed jets from detector level to particle level [38], as opposed to the parton level. An offset correction is also applied to account for the extra energy clustered in jets from the presence of additional proton–proton interactions (in-time or out-of-time pileup) within the same or neighboring bunch crossings. The overall jet-energy corrections depend on the η and p_T values of jets, and are applied as multiplicative factors to the four-momentum vector of each jet. These factors range between 1.0 and 1.2, and are approximately uniform in η . The jets accepted for analysis are required to satisfy $p_T > 50 \text{ GeV}$ and $|\eta| < 2.5$. In addition, all jet axes are required to be separated by $\Delta R > 0.4$ from those of lepton candidates from $Z \rightarrow \ell^+\ell^-$ decays. From MC studies, it is found that the selection efficiency of $Z + \text{jets}$ candidates is almost independent of jet multiplicity.

5. Observable quantities

The observable quantities used to describe the properties of $Z + \text{jets}$ events are the differential cross sections as functions of the azimuthal angles $\Delta\phi(Z, j_i)$ between the transverse momentum vectors of the Z boson and the i th leading jet in the event; the azimuthal angles among the three jets of leading $p_T \Delta\phi(j_i, j_k)$, with $i < k$, and i and k corresponding to 1, 2, or 3; and the transverse thrust τ_T , defined as [17]

$$\tau_T \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_T|}{\sum_i p_{T,i}}, \quad (1)$$

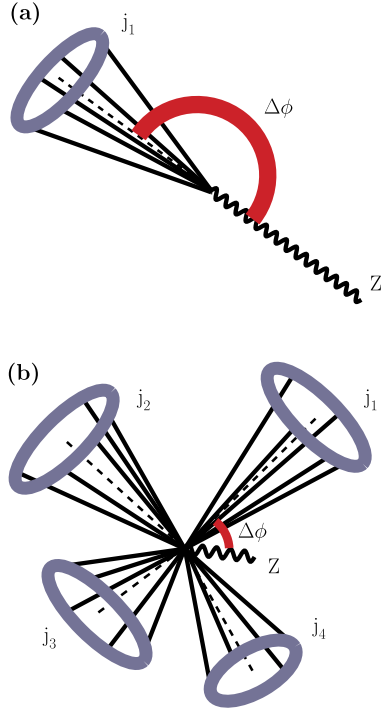


Fig. 1. Topology of Z + jets events: (a) for $\ln \tau_T \rightarrow -\infty$ and $\Delta\phi(Z, j_1) \rightarrow \pi$; (b) for $\ln \tau_T \rightarrow -1$ and $\Delta\phi(Z, j_1) \ll \pi$.

where the four-momenta of the Z boson and the jets are used as inputs to calculate τ_T , with $\vec{p}_{T,i}$ being the transverse momentum vector of object i , and the sum running over the Z and each accepted jet in the event. The unit vector \vec{n}_T that maximizes the sum, and thereby minimizes τ_T , is called the thrust axis. In the limit of the production of back-to-back Z + 1-jet events, τ_T tends to zero (Fig. 1(a)). With additional jet emission (i.e. the appearance of a second jet), the values of thrust increase. Thrust is most sensitive to specifics of modeling of two-jet and three-jet topologies, while it is less sensitive to QCD modeling of larger jet multiplicities. For clarity of presentation, we display results in terms of $\ln \tau_T$ rather than τ_T . The largest possible value is reached in the limit of a spherical, isotropically distributed event, where $\ln \tau_T \rightarrow \ln(1 - 2/\pi) \approx -1$ (Fig. 1(b)). In this limiting case the term $2/\pi$ originates from the uniform azimuthal distribution of the transverse momenta.

To investigate the dependence of the topological properties on the complexity of the final state, the events are categorized as a function of jet multiplicity. In particular, the azimuthal distributions are reported in inclusive bins of one, two, or three jets. Furthermore, the phase space is characterized according to the p_T of the Z boson, and measurements are performed either for all p_T^Z or in the region of $p_T^Z > 150$ GeV. Figs. 2 and 3 show, respectively, the distributions in the associated jet multiplicity and the p_T of $\mu^+\mu^-$ and e^+e^- systems for ≥ 1 jet events, prior to background subtraction. Both sets of distributions are presented at the detector level, and are within statistical uncertainty of the MC predictions for DY + jets, $t\bar{t}$, and other electroweak (EW) background sources. It should be noted that p_T^Z refers to the transverse momentum of the Z boson, following background subtraction and unfolding of detector effects.

6. Analysis procedure and systematic uncertainties

The analysis procedure consists of the following steps: $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ candidates are selected as described in Section 4; the

background is then subtracted and the resulting distributions are unfolded to the particle level; finally, the two channels are combined. The dominant sources of systematic uncertainty arise from uncertainties in jet-energy scale, resolution of jet p_T , background subtraction, and the unfolding procedure. Individual steps of the analysis procedure are detailed below.

The Z + jets candidates include several sources of SM background (Fig. 2), which are subtracted using predictions of the MADGRAPH MC event generator. The dominant background is from $t\bar{t}$ production, and is about 1.1%, 4%, and 8%, for the $N_{\text{jets}} \geq 1$, ≥ 2 , and ≥ 3 inclusive bins of jet multiplicity. An independent evaluation of the background from $t\bar{t}$ events is also obtained from an $e\mu$ control sample in data, which is selected by requiring the presence of an electron and a muon of opposite charge, but otherwise using the same criteria as used for selecting the Z + jets events. For each jet multiplicity bin, the estimates obtained from data and MC simulation agree within 6%. The two estimates are consistent, given the uncertainties on the integrated luminosity (2.2%) [39] and on the $t\bar{t}$ cross section (6%) [25]. Background originating from dibosons is 0.06%, 0.06% and 0.01% for the WW, WZ and ZZ channels, respectively. The contribution from $Z \rightarrow \tau\tau$ is $< 0.08\%$, largely because of the requirement on the Z mass of $71 < m_{\ell\ell} < 111$ GeV. Contributions from W + jets to the two-electron final state are estimated to be 0.1%, and $< 0.1\%$ to the two-muon channel. The contribution from single top quark production is estimated as $< 0.1\%$. Background from multijet production, estimated using dilepton pairs of same electric charge, is found to be negligible. A total uncertainty of 10% is assigned to the expectation from all background sources. The limited contribution of backgrounds to the Z boson candidate sample is reflected in a $< 1\%$ uncertainty on the final measurement.

The particle level four-momentum vector of a lepton is computed in the MC simulation by adding the four-momentum vectors of any photons found within a radius of $\Delta R = 0.1$ of each lepton axis to the four-momentum vector of the lepton. For the observables of interest in this analysis, the use of this cone size makes the electron and muon channels essentially the same at the particle level. In this way, the difference in final-state radiation in the $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ channels is accounted for and the two channels can then be directly combined. The particle level jets in MC events are reconstructed by clustering the generated stable particles (after hadronization) using the same anti- k_T algorithm, with a parameter $R = 0.5$, as done in data. The selection criteria used in data are also applied to particle level leptons and jets: the two leading leptons are required to have $p_T > 20$ GeV and $|\eta| < 2.4$, while the jets must have $p_T > 50$ GeV and $|\eta| < 2.5$. An angular separation of $\Delta R(\ell, j) > 0.4$ is also required between the two leading leptons and any accepted jet. Finally, the unfolded distributions from the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels are combined at the level of covariance matrices using the best linear unbiased estimator [40].

The background-subtracted, detector level distributions are mapped to the particle level by correcting for effects of detector resolution and efficiency. Migration of events among bins of inclusive jet multiplicity can be caused by detector resolution, especially from the mismeasurement of jet p_T . For example, an event containing a Z boson produced in association with N jets at the particle level, can migrate to the $N + 1$ jets final state as a result of detector resolution. The opposite effect can also occur leading to loss of events that migrate out of the geometric and kinematic acceptance. Such migrations correspond to as much as 30% and are treated in the detector unfolding procedure summarized below. Detector effects are expressed through a response matrix, which is determined from MC simulation, separately for each lepton flavor and each observable, by associating the particle level values

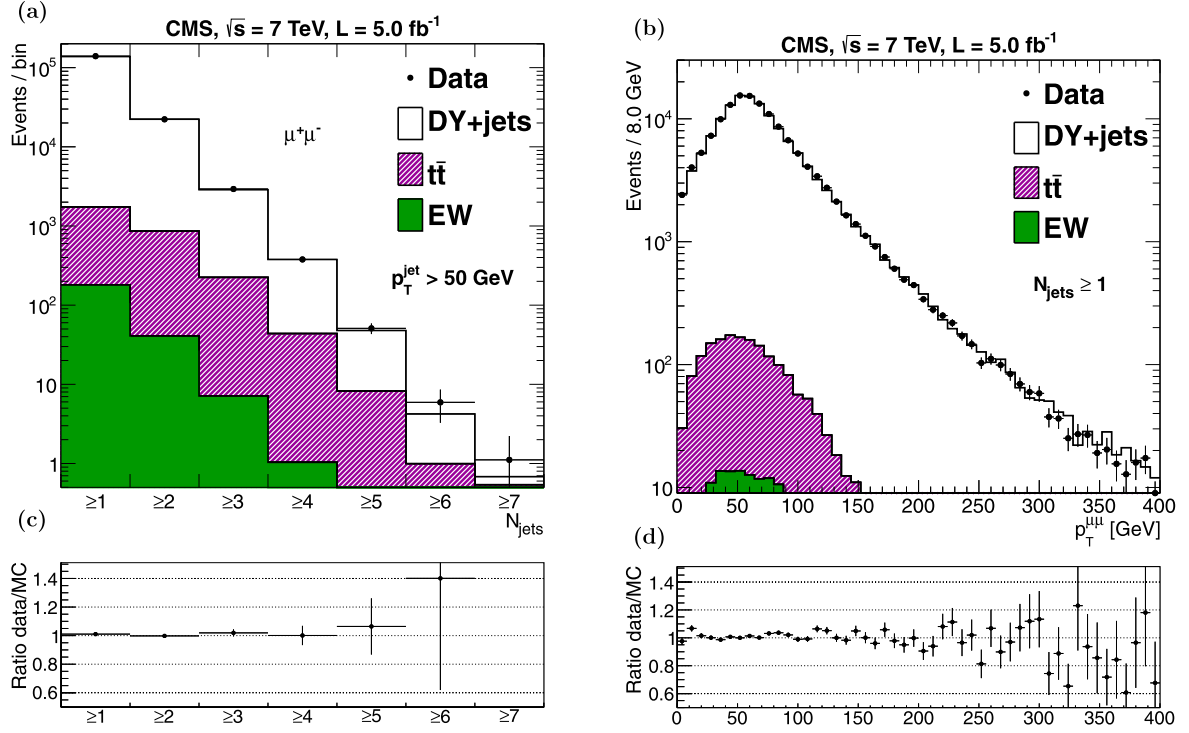


Fig. 2. Distributions for $Z \rightarrow \mu\mu$ candidate events in data, compared with expectations from simulated signal and background contributions using MADGRAPH simulations normalized to the integrated luminosity of the data: (a) as a function of associated jet multiplicity N_{jets} , and (b) as a function of p_T of the dimuon pair ($p_T^{\mu\mu}$) for $N_{\text{jets}} \geq 1$. The dibosons WW, WZ, ZZ and W + jets backgrounds are collectively denoted as EW in the legends. The plots in (c) and (d) show the ratios of the data to predictions from MC. The error bars on the data points represent only their statistical uncertainties and do not include systematic effects.

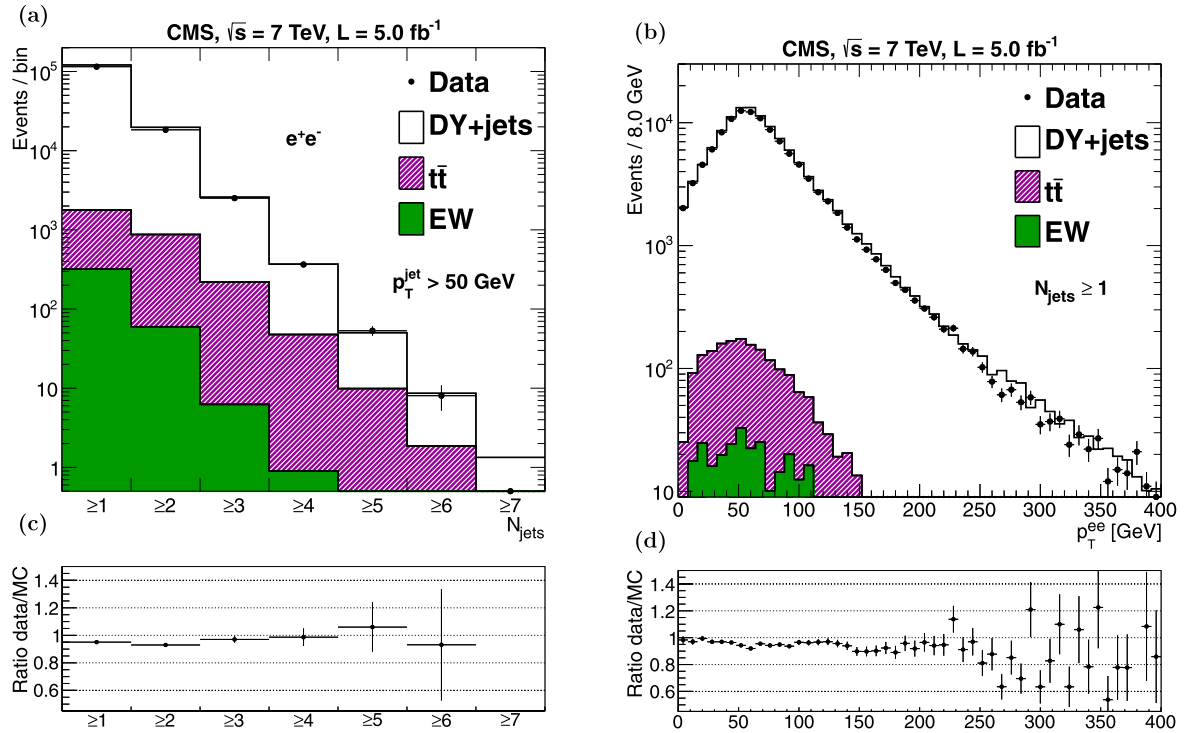


Fig. 3. Distributions for $Z \rightarrow ee$ candidate events in data, compared with expectations from simulated signal and background contributions using MADGRAPH simulations normalized to the integrated luminosity of the data: (a) as a function of associated jet multiplicity N_{jets} , and (b) as a function of p_T of the dielectron pair (p_T^{ee}) for $N_{\text{jets}} \geq 1$. The dibosons WW, WZ, ZZ and W + jets backgrounds are collectively denoted as EW in the legends. The plots in (c) and (d) show the ratios of the data to predictions from MC. The error bars on the data points represent only their statistical uncertainties and do not include systematic effects.

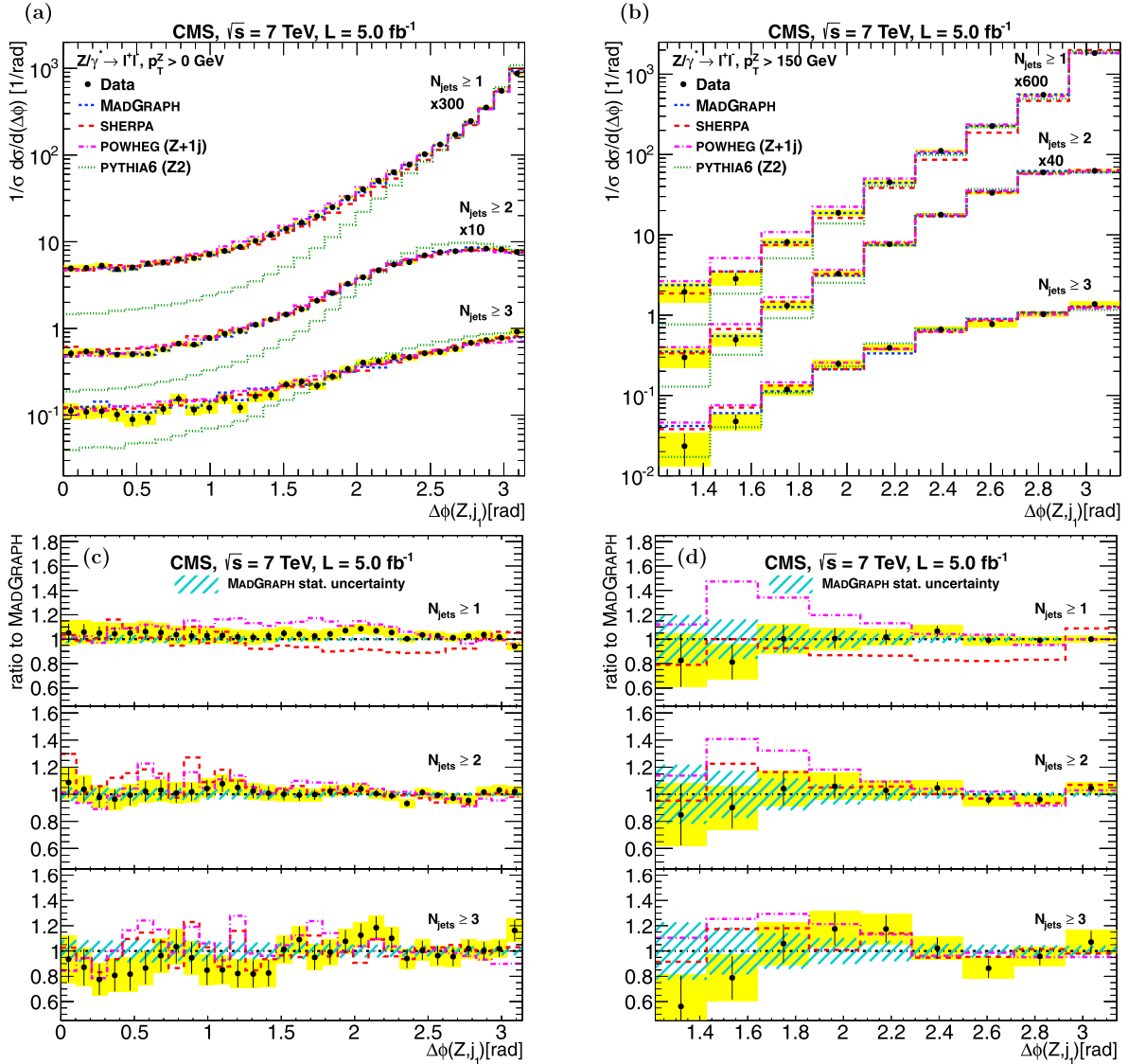


Fig. 4. Normalized $\Delta\phi(Z, j_1)$ distributions for the leading jet in the inclusive jet multiplicity bins $N_{\text{jets}} \geq 1, \geq 2$, and ≥ 3 : (a) all p_T^Z and (b) $p_T^Z > 150$ GeV. Plots in (c) and (d) show the corresponding ratios of the data (solid points), and of other MC predictions, relative to MADGRAPH. The ratio for PYTHIA MC is not included in these plots. The error bars on the data points represent their statistical uncertainties, the solid yellow shaded band around the points represents the sum of statistical and systematic uncertainties taken in quadrature, while the cross-hatched (cyan) bands reflect the statistical uncertainties on the MADGRAPH calculations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

to their reconstructed quantities. Two alternative representations of the response matrix, one generated from MADGRAPH (baseline) and the other from SHERPA, are used in this procedure, and half of the difference of the propagated results is used to define their systematic uncertainty. The unfolding of data to the particle level is performed using the Singular Value Decomposition method [41], implemented in the RooUNFOLD package [42]. The total systematic uncertainty due to the unfolding procedure is $< 5\%$ for azimuthal correlations and $< 2\%$ for the thrust analysis.

Among the azimuthal observables, the distribution of $\Delta\phi(Z, j_1)$ has the largest systematic uncertainty. This variable is particularly sensitive to the jet-energy scale, which can affect jet multiplicity, and thus the acceptance of events that enter in the $\Delta\phi(Z, j_1)$ distribution. The uncertainty on jet-energy scale varies between 1 and 3% [37], and results in an uncertainty of 2–4% on the distribution in $\Delta\phi(Z, j_1)$, increasing monotonically for decreasing angles. The impact from the resolution on p_T is estimated by changing

jet resolutions by $\pm 10\%$ (corresponding to about one standard deviation) [37], and comparing the unfolding correction before and after these changes. This yields a dependence of $\approx 1\%$ in the normalized azimuthal distributions. The uncertainty from pileup is estimated by changing in simulation the number of generated minimum-bias interactions by $\pm 5\%$. The resulting uncertainty is 4% for $\Delta\phi(Z, j_1) \approx 0$, which decreases to a negligible uncertainty for $\Delta\phi(Z, j_1) \approx \pi$. The overall systematic uncertainty on $\Delta\phi(Z, j_1)$ is about 5–6% at values of $\Delta\phi(Z, j_1) \approx 0$ and about 2% at values close to π .

The dominant systematic uncertainty on the thrust distribution, which corresponds to about 2%, is from the uncertainty in jet-energy scale, and can be understood as follows. When the energy scale is increased, more jets enter the two sums in Eq. (1), and both sums tend to shift to larger values. Conversely, when the jet-energy scale is decreased, their values decrease. The contribution from uncertainty in jet-energy resolution is found to affect

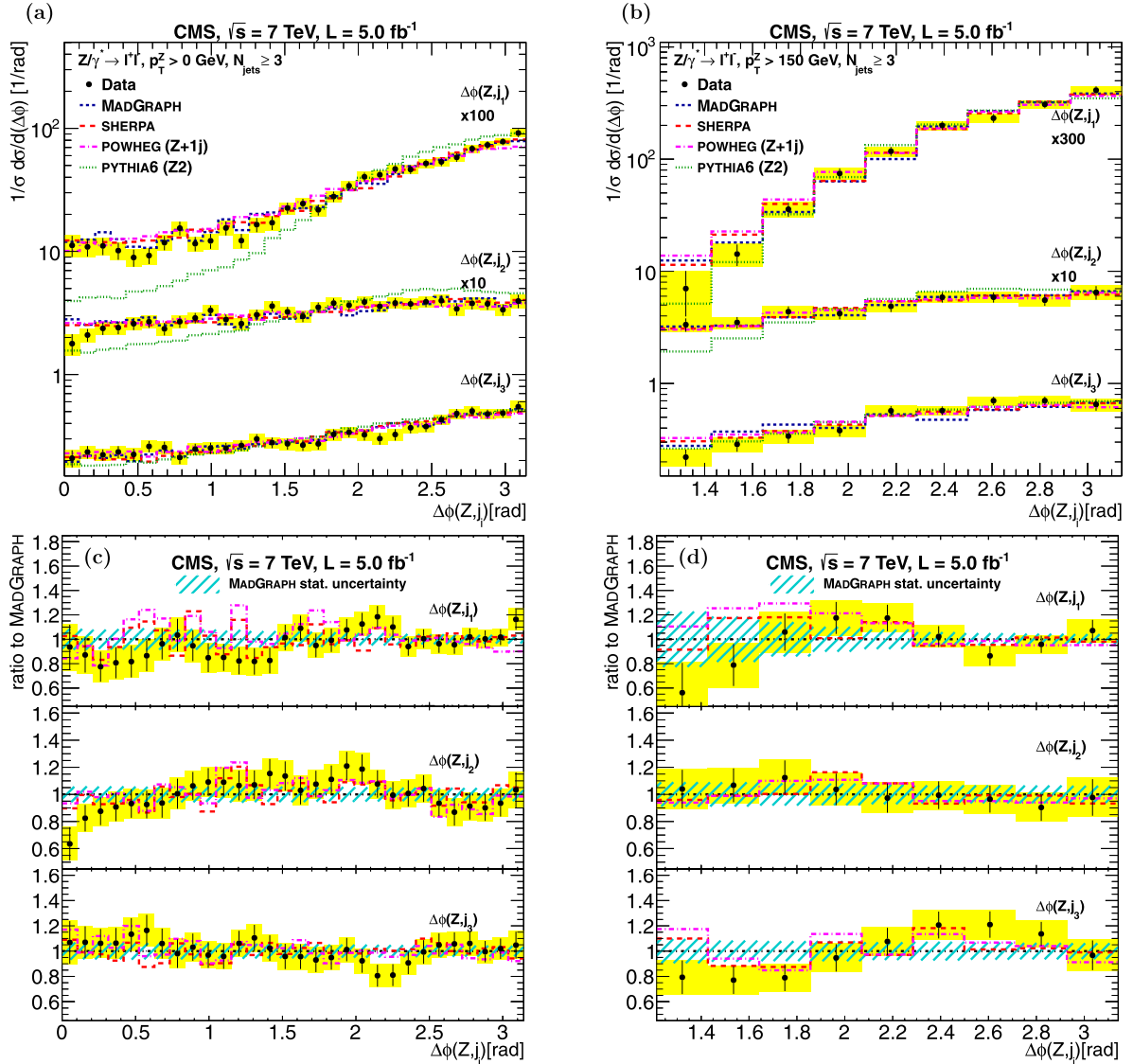


Fig. 5. Normalized $\Delta\phi(Z, j_i)$ distributions for the inclusive $N_{\text{jets}} \geq 3$ jet multiplicity bin: (a) all p_T^Z and (b) $p_T^Z > 150$ GeV. Plots in (c) and (d) show the ratios of the data and other MC predictions, relative to MADGRAPH, as described in Fig. 4.

the transverse thrust by 1%, and the uncertainties from selection efficiencies are $< 2\%$ for the entire range of $\ln \tau_T$, while the uncertainties from pileup and background subtraction have negligible impact. The first conclusion is implied in Eq. (1), as soft additional pileup energy added to the hard jets contributes simultaneously to both the numerator and denominator and, to first order, cancels in the ratio. The second conclusion follows from the fact that the transverse thrust is measured in the inclusive $Z + \geq 1$ -jet sample, where the signal purity is almost 99%, and background subtraction has therefore only a minimal impact on the measurement of $\ln \tau_T$.

For $p_T^Z > 150$ GeV the uncertainties on the azimuthal variables and on $\ln \tau_T$ are evaluated following the same procedure as described above. However, in addition to the uncertainties originating from previously discussed effects, the statistical limitations of the MC samples become important and the systematic uncertainty on the result therefore increases. The impact of the uncertainties on the electron and muon selection efficiencies due to energy scale, trigger and resolution has been assessed and found to be negligible.

7. Results

The corrected differential cross sections (normalized to unity) are compared to the predictions of MADGRAPH, SHERPA, POWHEG $Z + 1$ -jet (NLO), and PYTHIA generators. The differential cross sections in the $\Delta\phi$ and $\ln \tau_T$ variables are divided by the total $Z + \text{jets}$ cross section for the range defined by the lepton and jet kinematic selection criteria, i.e. $p_T > 20$ GeV and $|\eta| < 2.4$ for leptons, and $p_T > 50$ GeV and $|\eta| < 2.5$ for jets, and $\Delta R > 0.4$ for jet–lepton separation. The distributions in data and MC are therefore normalized to unity. Fig. 4 shows $\Delta\phi(Z, j_1)$ as a function of jet multiplicity for inclusive $Z + N_{\text{jets}}$ production, with $N_{\text{jets}} \geq 1, 2$, and 3. Figs. 5 and 6 show the $\Delta\phi(Z, j_i)$ and $\Delta\phi(j_i, j_k)$ distributions, where i, k represent jet indices in order of decreasing p_T , for $N_{\text{jets}} \geq 3$. For the sake of comparison, the $\Delta\phi(Z, j_1)$ results for $N_{\text{jets}} \geq 3$ from Fig. 4 are also included in Fig. 5. These distributions characterize essentially all the azimuthal correlations in the $N_{\text{jets}} \geq 3$ inclusive jet multiplicity bin. Finally, the $Z + \text{jets}$ distributions in $\ln \tau_T$ are presented in Fig. 7. For both azimuthal and $\ln \tau_T$ distributions, the sum of statistical and systematic uncertainties

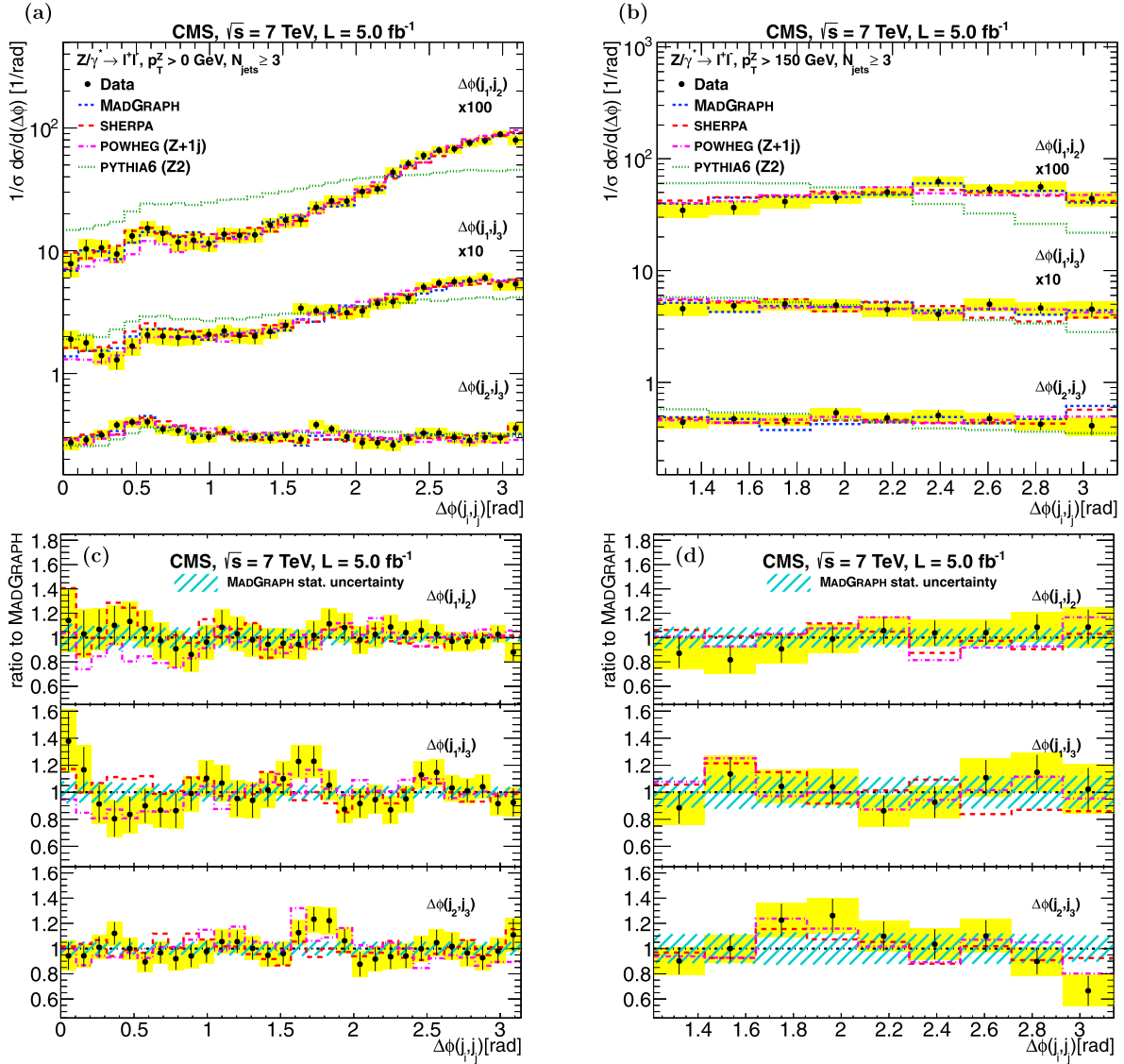


Fig. 6. Normalized $\Delta\phi(j_i, j_j)$ distributions for the inclusive $N_{\text{jets}} \geq 3$ jet multiplicity bin: (a) all p_T^Z and (b) $p_T^Z > 150$ GeV. Plots in (c) and (d) show the ratios of the data and other MC predictions, relative to MADGRAPH, as described in Fig. 4.

taken in quadrature are presented as solid yellow shaded bands. The statistical uncertainty from the MADGRAPHMC is displayed as a cross-hatched band for each distribution.

Overall, the measured distributions in $\Delta\phi(Z, j_1)$ agree within uncertainties with the predictions from MADGRAPH. The predictions from SHERPA underestimate the measured distributions by about 10% whereas POWHEG predictions overestimate by about 10%. The disagreements with SHERPA and POWHEG (as well as between the two models) become less pronounced at larger inclusive jet multiplicities (Fig. 4). For $N_{\text{jets}} = 1$, the Z boson and the accompanying parton are completely correlated, and $\Delta\phi(Z, j_1) \approx \pi$ (Fig. 1(a)). When $\Delta\phi(Z, j_1) \ll \pi$, the presence of additional hard QCD radiation is implied. Certain configurations of jets with $\Delta\phi(Z, j_1) < \pi/2$ probe events where the Z boson is in the same hemisphere as the leading jet, and the \vec{p}_T of the Z boson is therefore balanced by at least two (or more) subleading jets emitted in the opposite hemisphere (Fig. 1(b)). The importance of the multiparton LO + PS approach, as reflected in MADGRAPH and SHERPA, can be seen when the data are compared to stand-alone PYTHIA at $\Delta\phi(Z, j_1) < 2.5$ and $N_{\text{jets}} \geq 1$. For higher jet multiplicities of

$N_{\text{jets}} \geq 2$ and ≥ 3 , the distribution in $\Delta\phi(Z, j_1)$ becomes more isotropic, although a strong correlation remains at $\Delta\phi = \pi$.

Within uncertainties, good agreement is observed between the data and MADGRAPH, SHERPA, and POWHEG event generators for $N_{\text{jets}} \geq 3$. Stand-alone PYTHIA is also consistent with the distributions in $\Delta\phi(Z, j_3)$ and $\Delta\phi(j_2, j_3)$. In PYTHIA, these high-multiplicity configurations are generated exclusively from the PS contribution. The important role of the PS approximation in modifying the kinematics predicted from fixed-order calculations is emphasized in POWHEG, where its predictive power in a multijet environment ($N_{\text{jets}} \geq 3$) is evident in Figs. 4–6. While POWHEG represents an NLO prediction only for the leading jet, and additional radiation is modeled exclusively using parton showers, good agreement is observed for data with $N_{\text{jets}} \geq 3$.

For the region $p_T^Z > 150$ GeV, the $\Delta\phi(Z, j_1)$ distributions become more isotropic as jet multiplicity increases. In addition, and contrary to the result for all p_T^Z , the angular distributions between the subleading jets $\Delta\phi(j_i, j_k)$ also become isotropic (Fig. 6(b)). The improved performance of PYTHIA in this region is consistent with the increased phase space available for parton emission. A similar

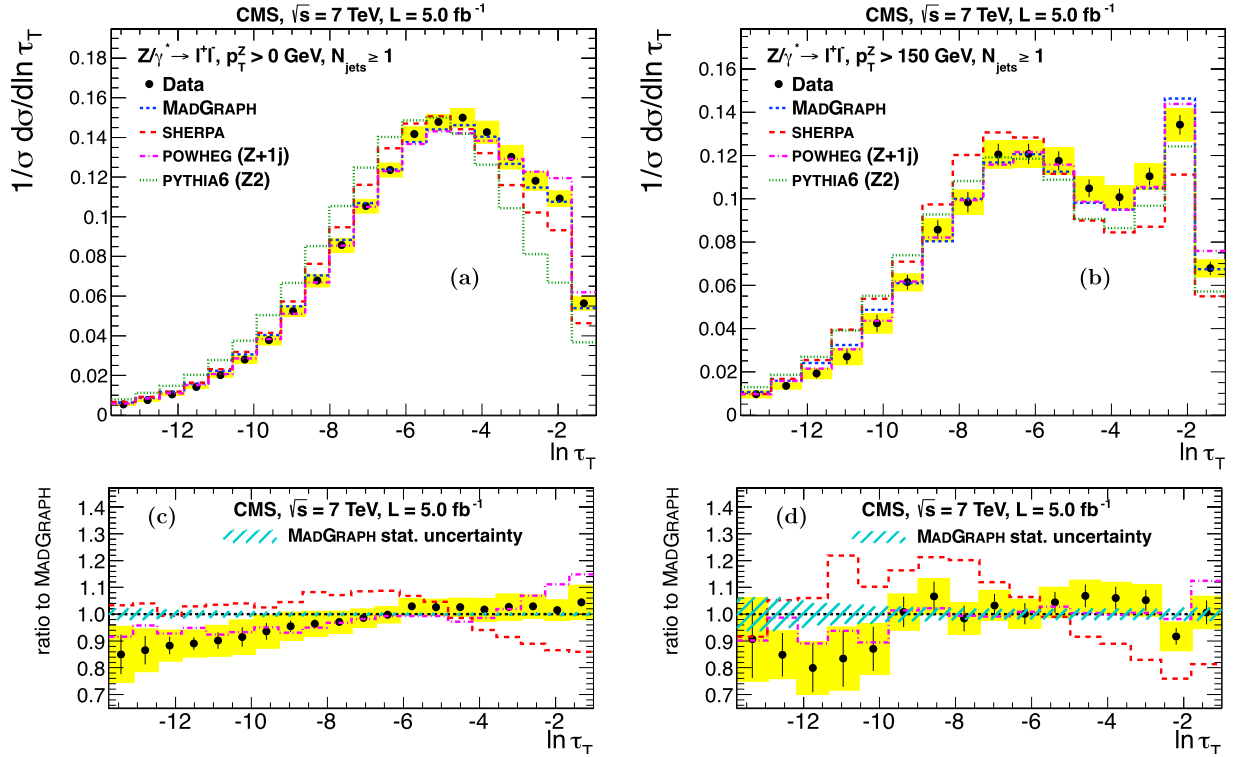


Fig. 7. Normalized distributions in $\ln \tau_T$ for (a) all p_T^Z and $N_{\text{jets}} \geq 1$ data, and (b) for $p_T^Z > 150 \text{ GeV}$ and $N_{\text{jets}} \geq 1$. Plots in (c) and (d) show the ratios of the data and other MC predictions, relative to MADGRAPH, as described in Fig. 4.

observation can be made for distributions in $\ln \tau_T$, which are discussed below. The level of agreement between PYTHIA and data for distributions in $\ln \tau_T$ improves for $p_T^Z > 150 \text{ GeV}$ (Fig. 7).

The corrected normalized differential distributions in $\ln \tau_T$ are displayed in Fig. 7. The distributions for large p_T^Z indicate an accumulation of events at values of $\ln \tau_T \approx -2$, as could be expected, because this region of phase space corresponds to contributions from events with a large spherical component, corresponding to production of two or more jets. Among the four examined models, POWHEG and MADGRAPH are more consistent with the data, being within 10% of the measured distributions, except at large negative values of $\ln \tau_T$, where ≈ 15 –20% deviations are observed. The level of agreement of SHERPA with data corresponds to 10–15% for most of the bins, while PYTHIA shows discrepancies of $> 20\%$. PYTHIA and SHERPA also predict too small values of $\ln \tau_T$, especially at values dominated by configurations in which the leading jet is produced back-to-back with the Z boson. This yields a larger proportion of back-to-back Z + 1-jet events relative to data at small $\ln \tau_T$, an effect that can also be observed in the $\Delta\phi(Z, j_1)$ distribution of Fig. 4.

8. Summary

This Letter reports studies of angular correlations among the objects in Z+jets final states. The measurements are based on data corresponding to an integrated luminosity of 5.0 fb^{-1} , collected with the CMS detector at the LHC in proton–proton collisions at $\sqrt{s} = 7 \text{ TeV}$.

Azimuthal correlations among the Z boson and the accompanying jets, $\Delta\phi(Z, j_i)$ and $\Delta\phi(j_i, j_k)$, are measured as functions of inclusive jet multiplicity ($N_{\text{jets}} \geq 1, \geq 2$, and ≥ 3). In addition, the transverse thrust event shape variable $\ln \tau_T$ is used to characterize the events. Two regions of phase space are probed: (i) all events, independent of p_T^Z , and (ii) the more highly boosted sub-

set of events with $p_T^Z > 150 \text{ GeV}$. The systematic uncertainties are smaller than those arising from statistical sources, which dominate in the extreme regions of phase space.

The data are compared with predictions from MADGRAPH, SHERPA, POWHEG Z+1-jet (at NLO), and stand-alone PYTHIA Z+1-jet (at LO). PYTHIA corresponds to the simplest model, and is used to gauge the importance of additional corrections from LO and NLO ME formulations that are interfaced with programs that evolve parton showers. Stand-alone PYTHIA provides an adequate description of event topologies when the phase space available for parton emission is large, e.g. for the highly boosted selection on p_T^Z . The MC models that combine multiparton QCD LO ME interfaced to parton shower evolution tend to agree with the data. The Z + 1-jet ME calculation (at NLO) provided by POWHEG shows agreement with data at large jet multiplicity in the entire phase space probed in this study, despite the fact that, beyond the subleading jet, additional radiation comes exclusively from parton showers.

The measurements presented in this study provide a detailed description of the topological structure of Z + jets production that is complementary to existing measurements of rates and associated jet multiplicities. As theoretical understanding evolves, these results can be used as additional probes of the validity of QCD predictions, while also providing confidence in the current MC models as useful tools for the description of SM processes and their application for determining background in searches for new phenomena.

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